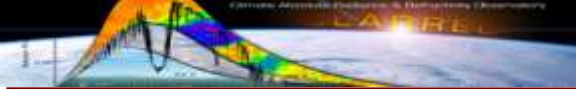




What Is CLARREO?

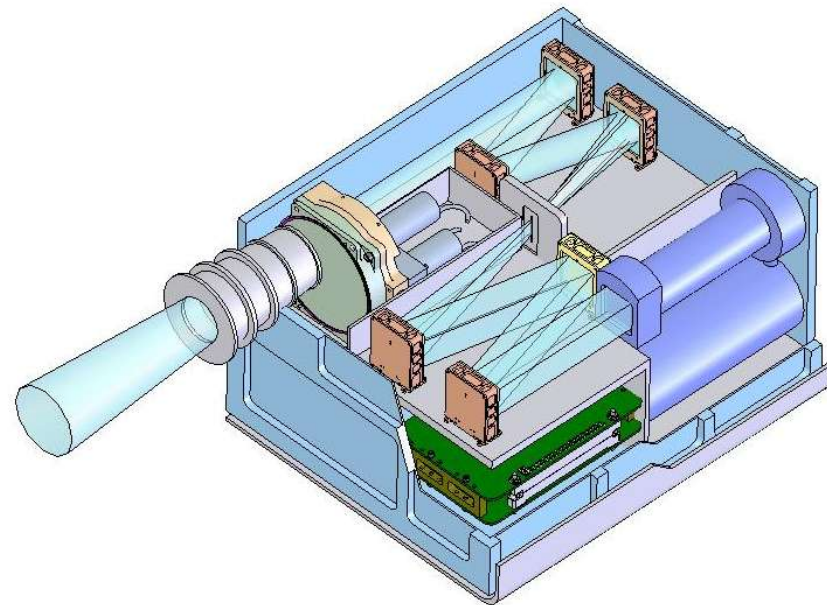
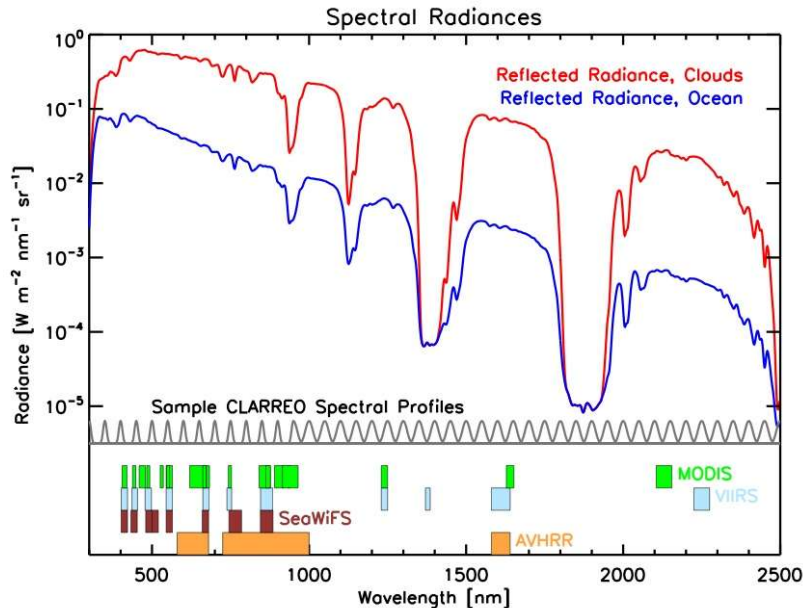
Climate Absolute Radiance and Refractivity Observatory

- Key mission element of the climate observing system recommended in the 2007 NRC Earth Science Decadal Survey
 - Initiate an unprecedented, high accuracy record of climate change that is tested, trusted, and necessary to provide sound policy decisions
- Intended to produce irrefutable climate records and to test, validate, and improve climate prediction models through exacting onboard traceability of instrument accuracy in
 1. Spectral reflected shortwave radiances (G. Kopp, K. Thome)
 2. Emitted infrared radiances (M. Mlynczak, J. Dykema)
 3. GPS radio occultation refractivities



LASP Visible/NIR Radiometry Studies

- Science Study
 - Define benchmark measurements needed for climate studies
 - Evaluate benefits of cross-calibrations
- Hyperspectral Imager Instrument Incubator Program (IIP)
 - Improve radiometric accuracy of Earth-viewing hyperspectral imager via direct solar cross-calibrations





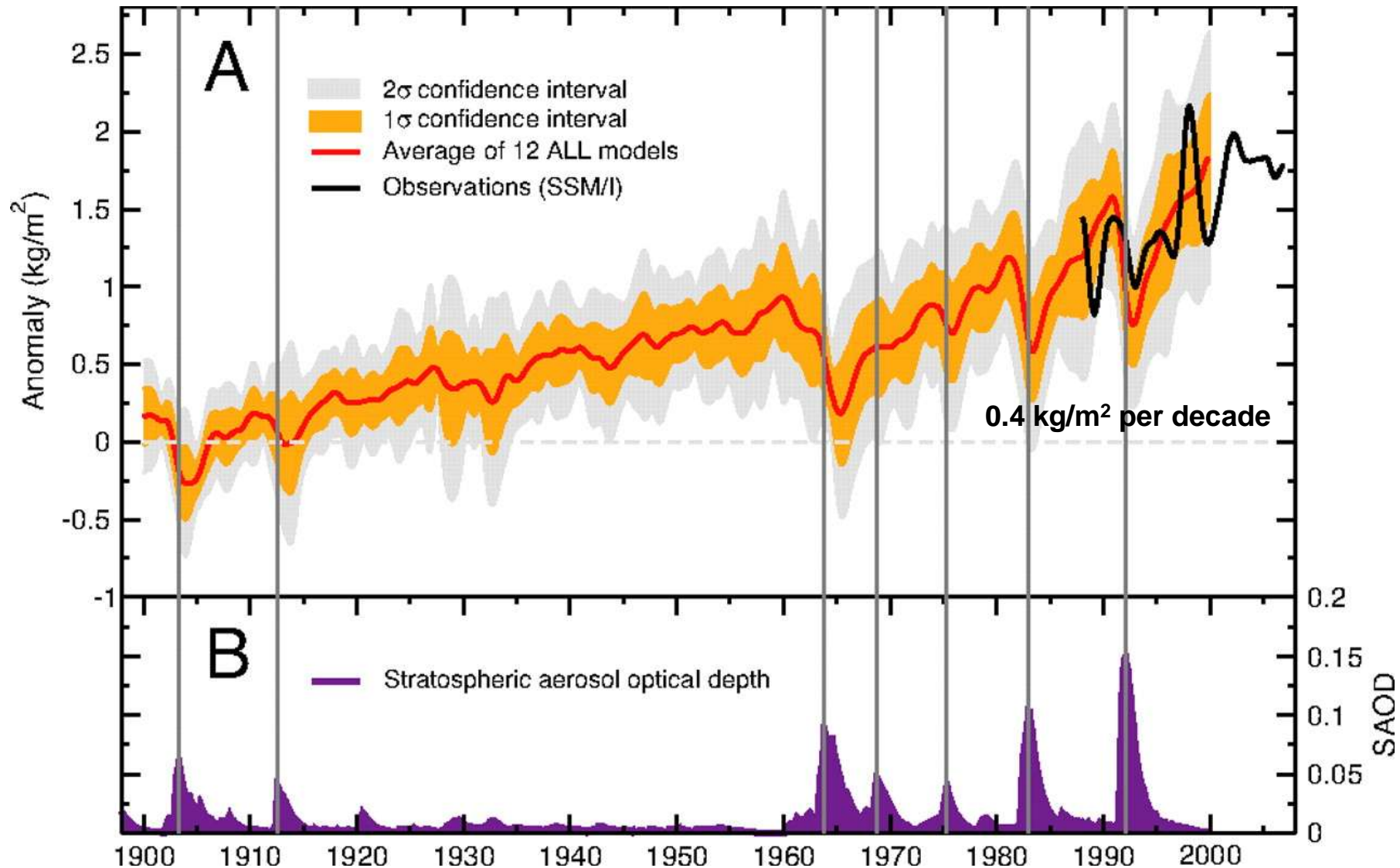
Science Studies

Determine requirements for CLARREO shortwave instruments

Detect climate change signal on decadal time scale

- Climate Benchmarking
 - Accuracy
 - Radiometric
 - Spectral
 - Stability
 - Spatial coverage and resolution
 - Spectral range and resolution
- Cross-Calibrations
 - Other on-orbit instruments that can benefit from cross-calibrations to improve accuracy
 - Other on-orbit instruments that can extend CLARREO coverage via cross-calibrations

Climate Fingerprinting: Water Vapor Feedback

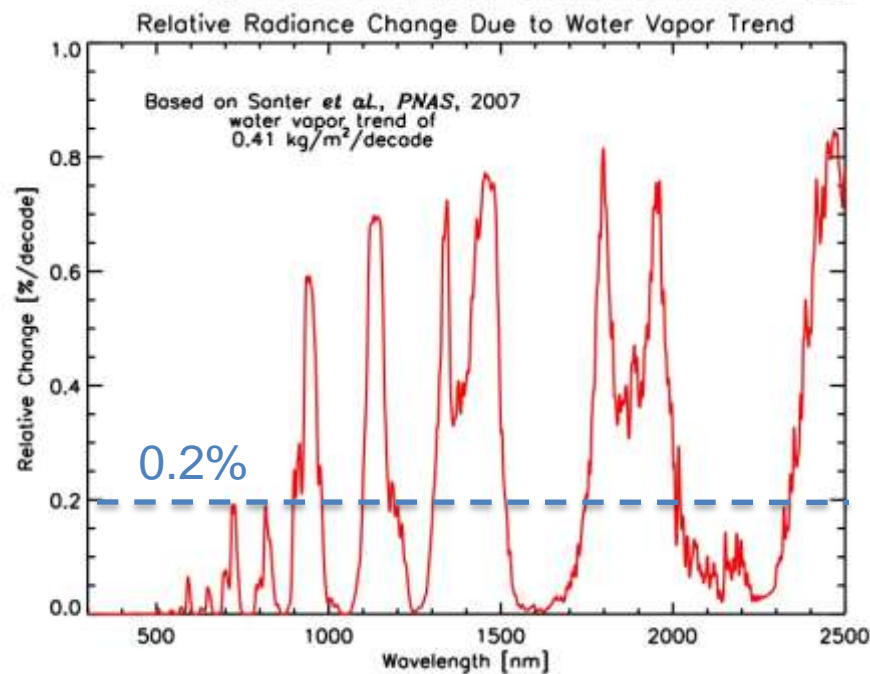
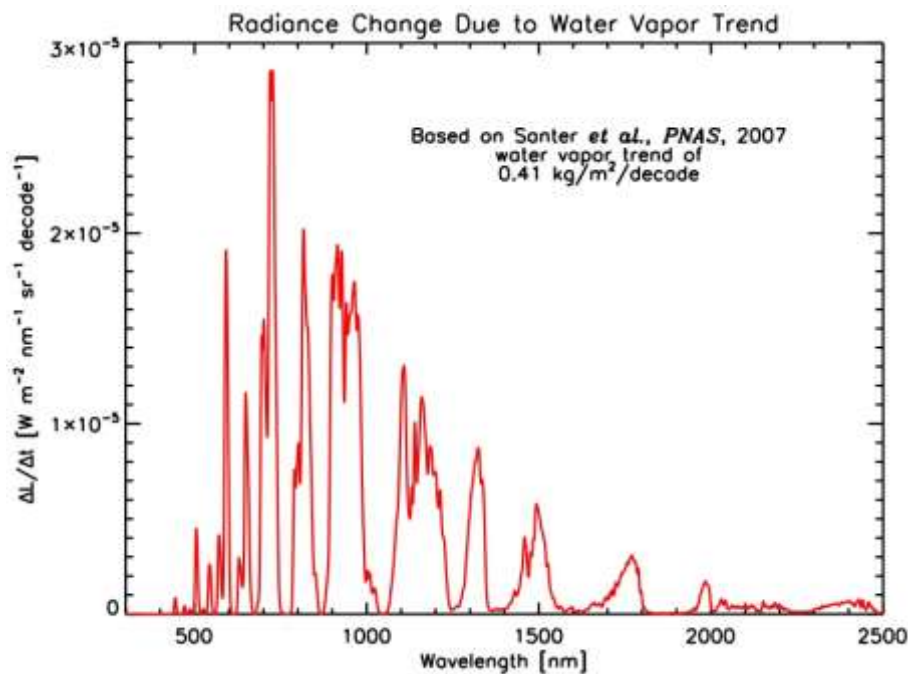
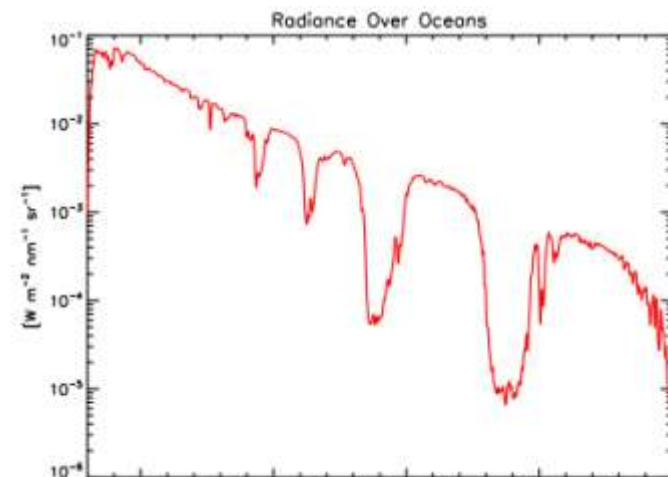


Santer et al., PNAS, 2007.



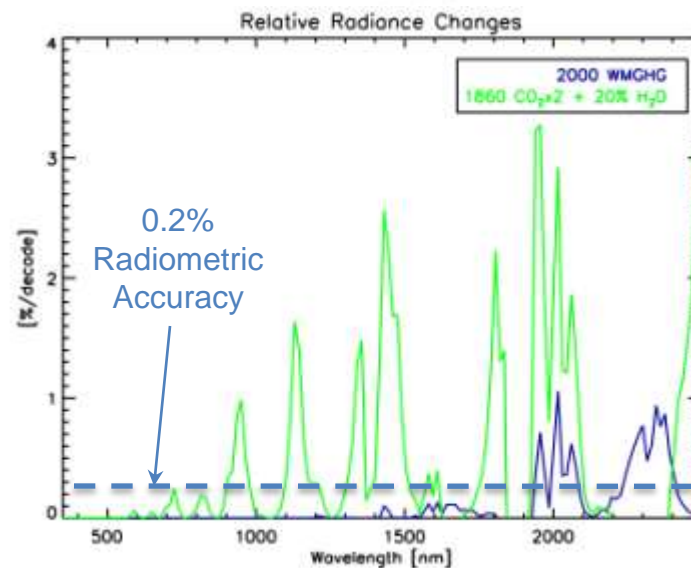
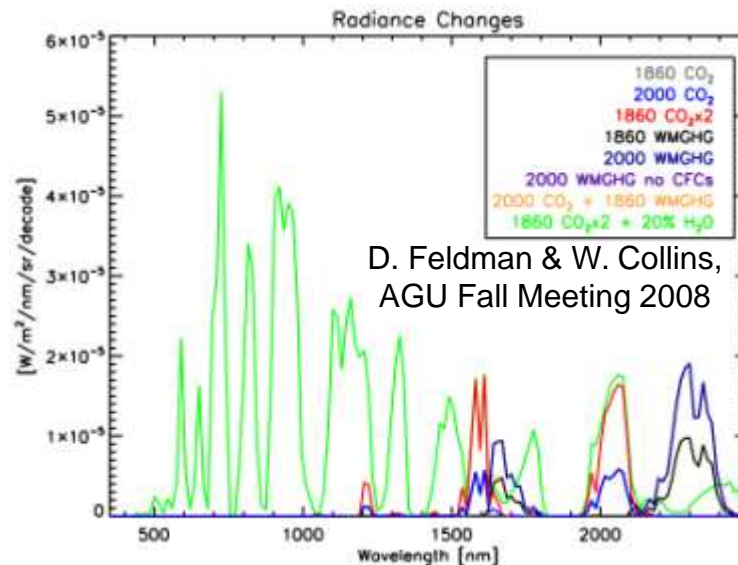
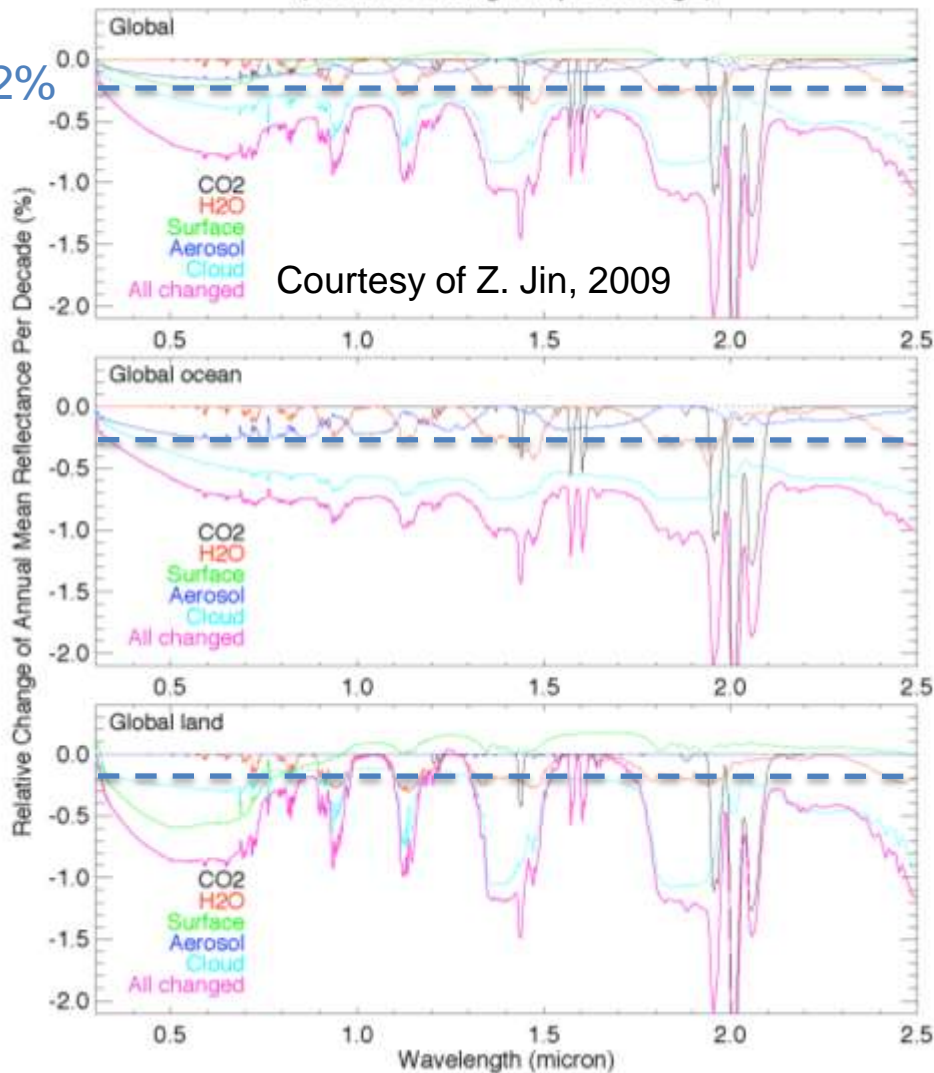
Sensitivity of Earth-Reflected Solar Radiance to Water Vapor

- MODTRAN simulations used to derive changes in outgoing top-of-atmosphere spectral radiance due to 0.4 kg/m^2 per decade trend
- Largest absolute changes (radiance is reduced) occur in the weak (sub-saturated) VNIR water band; largest fractional changes in the wings of the stronger SWIR bands

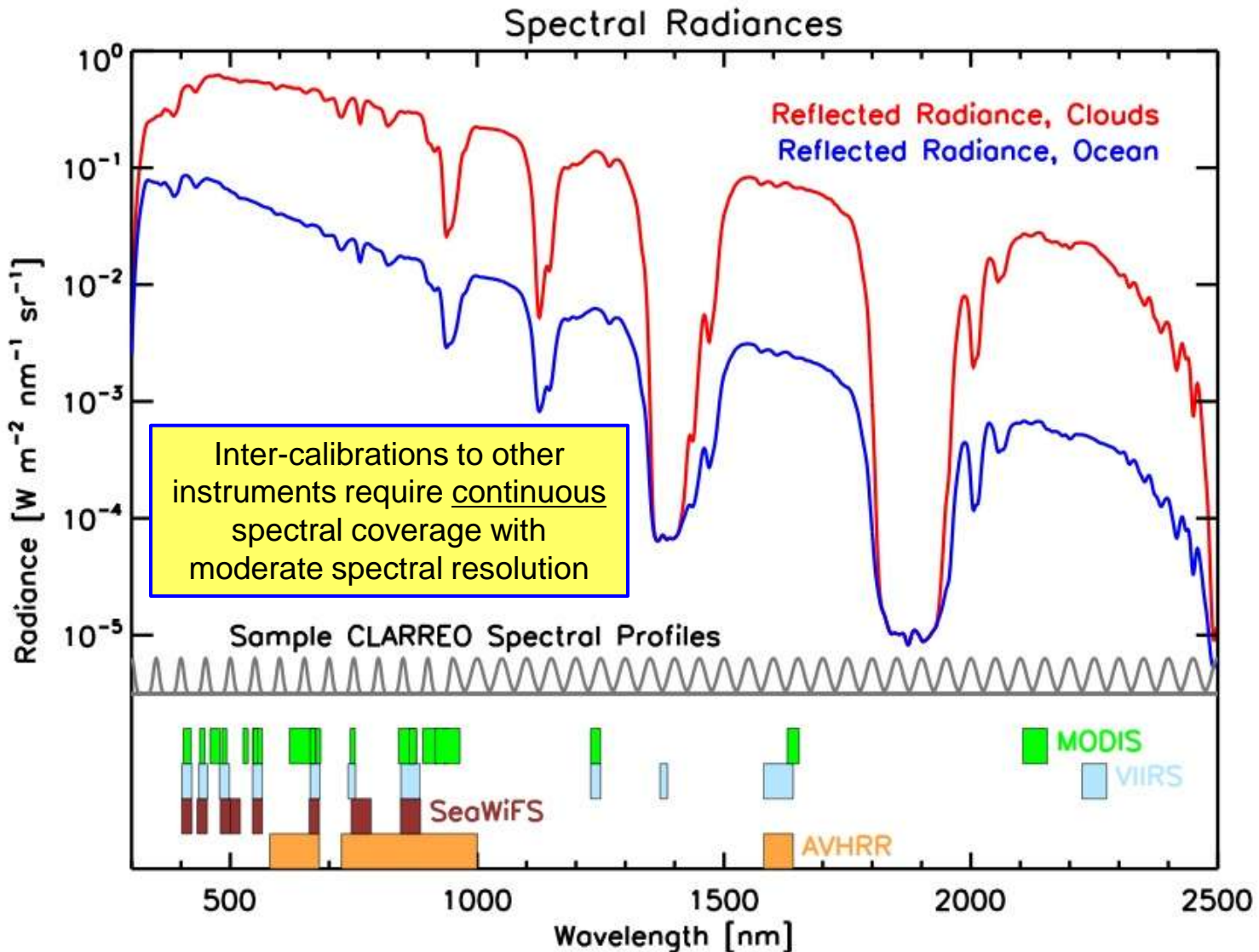


Modeled Climate Sensitivity Drives Radiometric Accuracy

Solar Spectral Signal For 1 Decade Climate Change
(Relative change in percentage)



Need Continuous Spectral Coverage & Moderate Resolution





Contiguous Spectral Measurements Constrain Aerosol Absorption

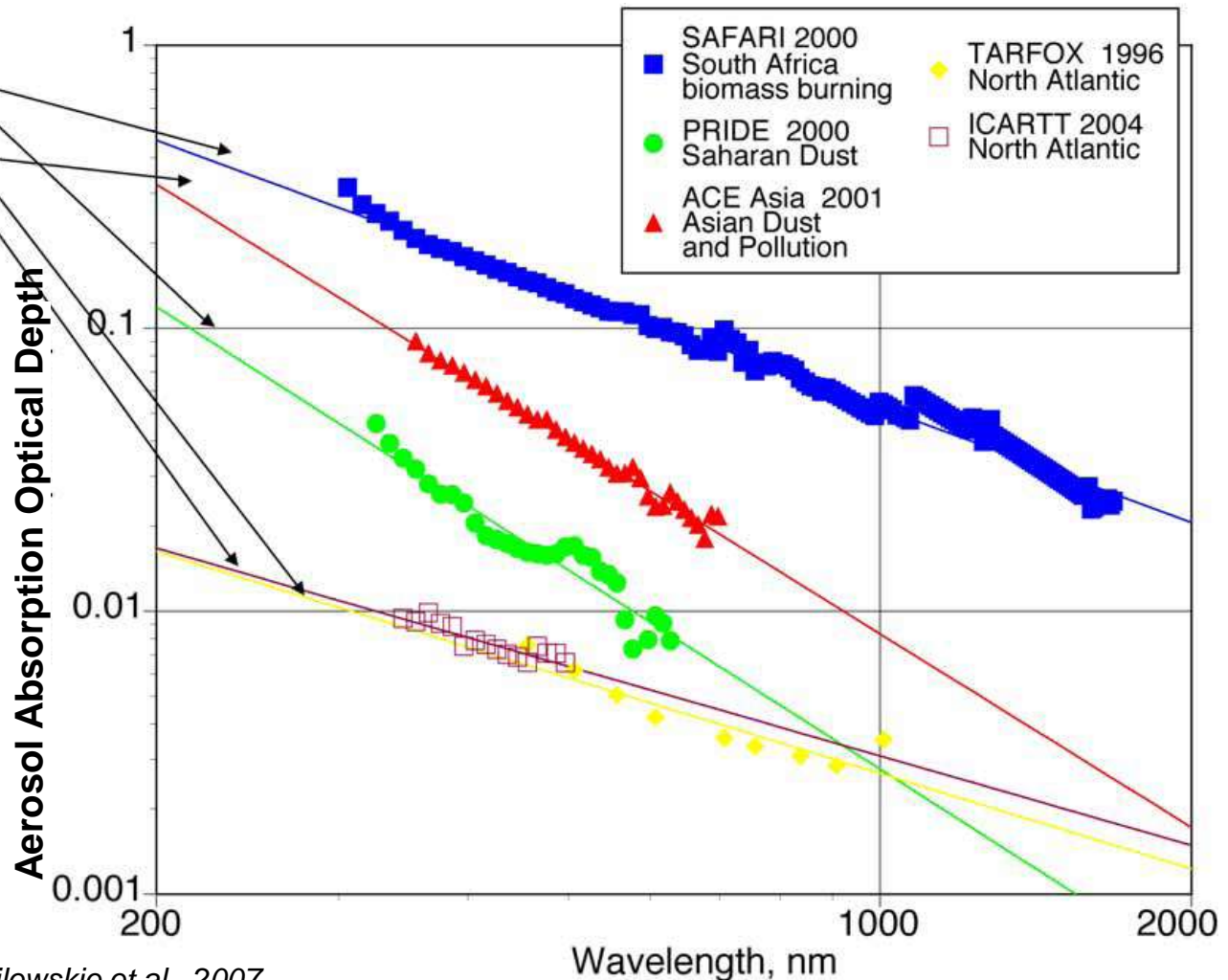
Slope of Power law fit (AAE)

SAFARI = 1.35 $R^2 = 0.98$
 PRIDE = 2.34 $R^2 = 0.92$
 ACE Asia = 2.27 $R^2 = 0.99$
 TARFOX = 1.12 $R^2 = 0.84$
 ICARTT = 1.05 $R^2 = 0.82$

$$\tau_a = \tau - \tau_0$$

➤ Dust: large particles, τ decreases slowly with wavelength.

➤ BC: small particles, rapid falloff in τ with wavelength.

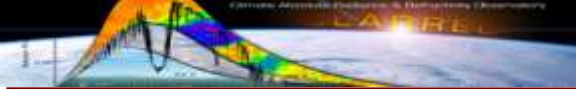


Bergstrom and Pilewskie et al., 2007.



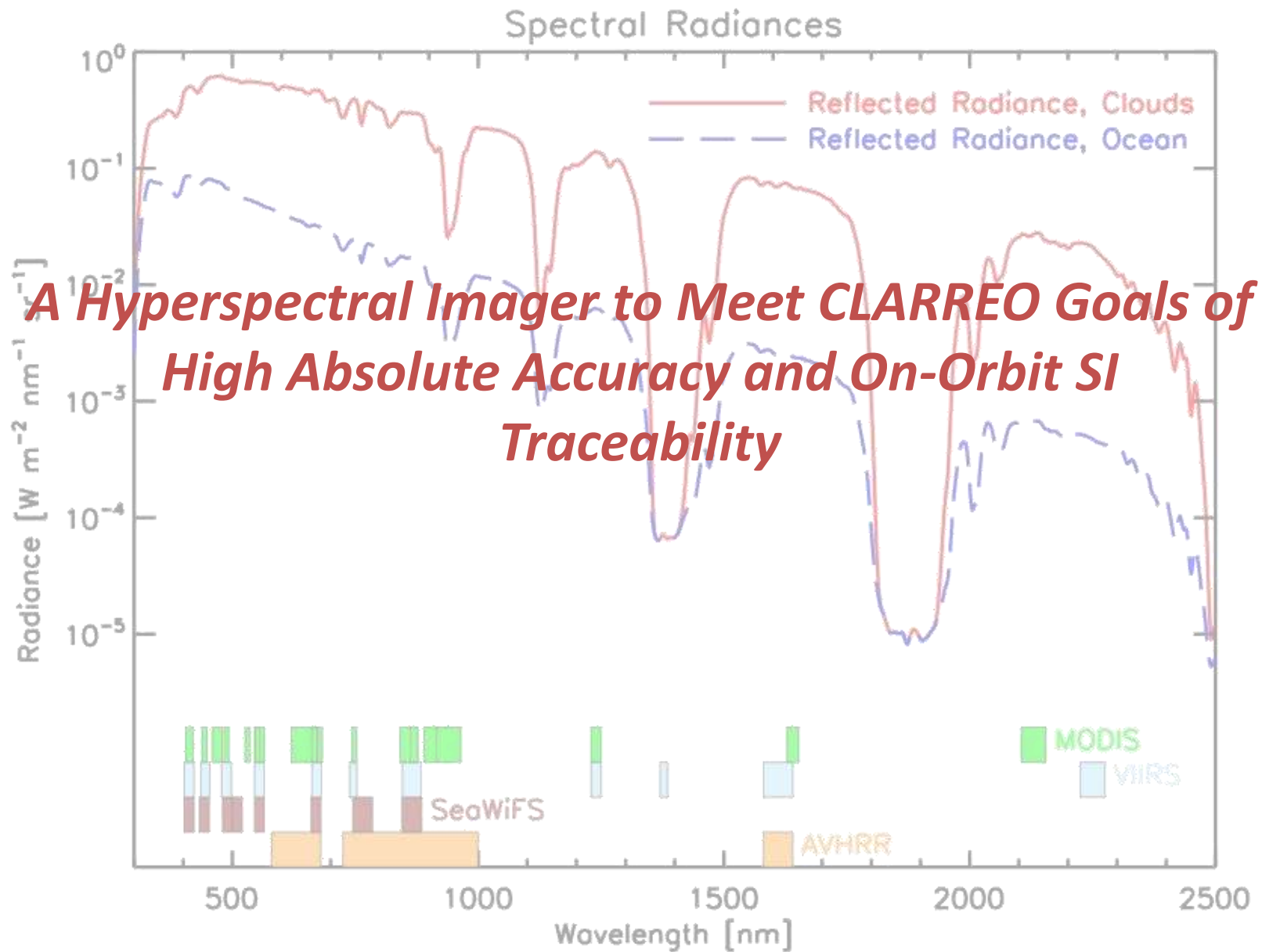
Cross-Calibrations Have Differing Requirements From Climate Benchmarking

| Requirement | Climate Benchmarking | Cross-Calibration |
|---------------------|--|---|
| Radiometry | 0.2% | ~0.5% (may not be limiting factor) |
| Spectral Resolution | ~10 nm | 2 - 10 nm |
| Spectral Range | continuous | continuous |
| Spatial Resolution | ~1 km | ~1 km |
| Spatial Range | 100 km | 100 km |
| Polarimetry | minimize for radiometry via optical design | helpful to estimate radiometric uncertainties |
| Orbit | Sun-Sync or Low Lat. | Precessing |



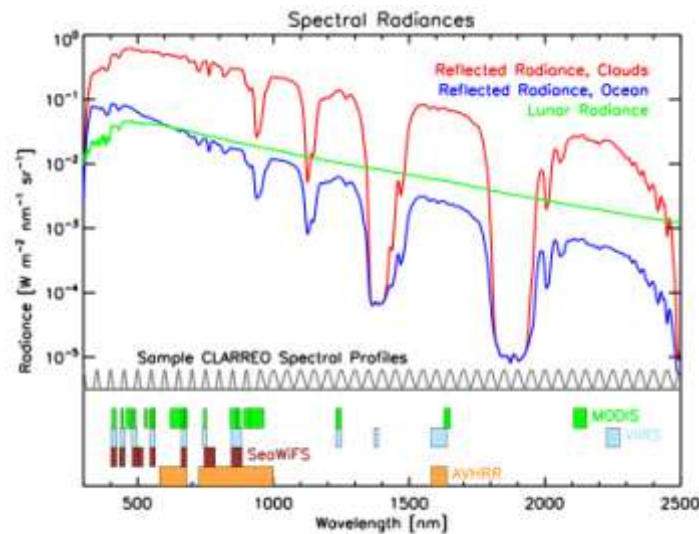
LASP Shortwave Study Requirements Summary

- Radiometric accuracy $\sim 0.2\%$ (1σ)
 - 0.5-1%/decade change in reflectance predicted by various models
- Continuous spectrum is required for climate benchmarking
 - Needed for cross-calibrations
 - Energy arguments: 50% absorption > 1400 nm
- Spectral resolution < 10 nm
 - Resolution makes little difference in distributed PCA variance
 - Need ~ 10 nm for cloud phase discrimination, surface characterization
 - Need < 10 nm for cross-calibrations
- Spatial sampling ~ 1 km IFOV with > 100 km range
 - Optimizes PP/IP approximations and spatial coverage
- Directional sampling can be nadir-oriented
 - Nadir bias $<$ Inter-annual variability



Want Improved Radiometric Accuracies in Visible/NIR

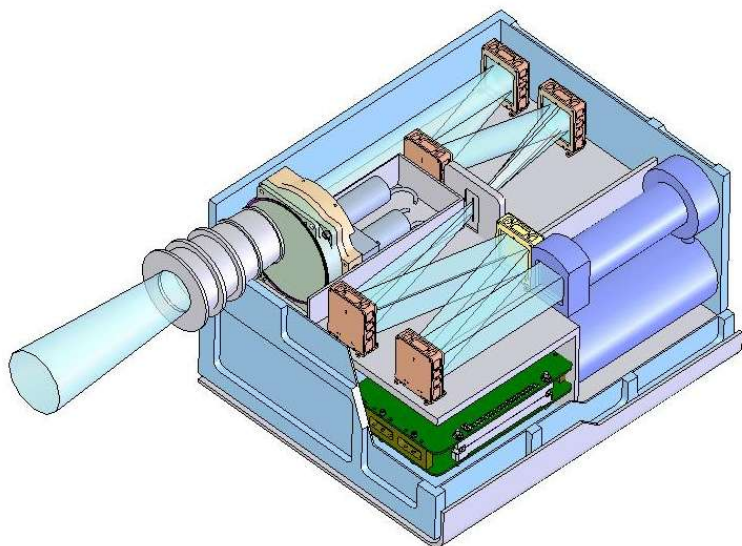
- Current instruments have >2% radiometric accuracy
 - Accuracy and stability rely on ground calibrations, on-board lamps, cross-calibrations, solar diffusers, or lunar observations



| Methods/Type of Calibration | Uncertainties | Constraints |
|--|--|---|
| Artificial Test Sites Absolute | <ul style="list-style-type: none"> Actual: 3.5% reflectance-based, 2.8% radiance-based Expected: 2.8% and 1.8% | <ul style="list-style-type: none"> Requires ground instrumentation Requires good atmospheric conditions Requires specific sensor operations |
| Stable Deserts Stability | <ul style="list-style-type: none"> Actual: 3% Expected: 1% with BRDF (bandpass dependent) | <ul style="list-style-type: none"> Requires non-cloudy images Requires specific sensor operations |
| The Moon Stability | <ul style="list-style-type: none"> Expected: <1% | <ul style="list-style-type: none"> Dynamic range is limited Req. specific operations & viewing |
| The Moon Absolute | <ul style="list-style-type: none"> Actual: 5-10% Expected: 1% | <ul style="list-style-type: none"> Dynamic range is limited Req. specific operations & viewing Requires low uncertainty calibration and radiometric verification of the moon |



Solar Cross-Calibration Achieves SW Radiometric Accuracy



Ratio of solar incoming to outgoing radiances benchmarks climate in shortwave

Ratio of reflected (outgoing) to incoming solar radiation measured to $<0.2\%$ ($1-\sigma$).

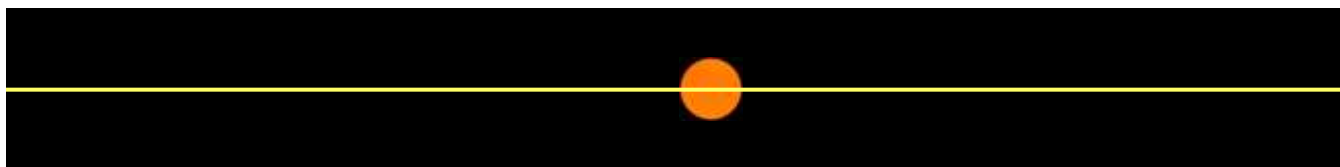
| Hyperspectral Imager Requirements | | |
|-----------------------------------|-------|-------|
| Parameter | Value | Units |
| Spatial Resolution | 0.5 | km |
| Spatial Range (cross-track) | 200 | km |
| Wavelength (min) | 300 | nm |
| Wavelength (max) | 2400 | nm |
| Spectral Resolution | 10 | nm |
| Relative Std Uncertainty | 0.2 | % |

Cross-calibration from Sun intended accuracy of 0.2% ($1-\sigma$).

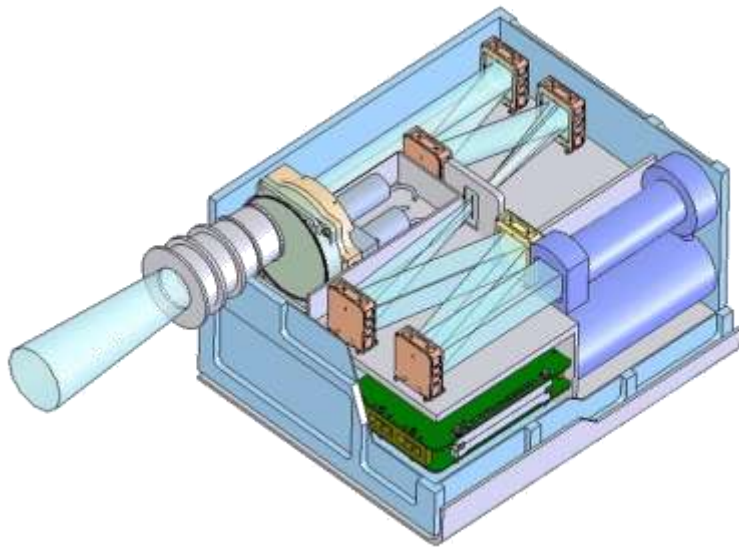
One or two spatial/spectral imagers cover 300-1000 and 1000-2400 nm.

Small (~ 2 -cm) telescope optics image the Earth onto spectrographs.

Radiance attenuation methods reduce intensity an accurately known amount, allowing cross-calibrations with Sun.



Earth-Viewing Shortwave Goals for IIP



| Hyperspectral Imager Requirements | | |
|-----------------------------------|-------|-------|
| Parameter | Value | Units |
| Spatial Resolution | 0.5 | km |
| Spatial Range (cross-track) | 200 | km |
| Wavelength (min) | 300 | nm |
| Wavelength (max) | 1050 | nm |
| Spectral Resolution | 10 | nm |
| Relative Std Uncertainty | 0.2 | % |

0.5 km (2.5 arcmin) IFOV



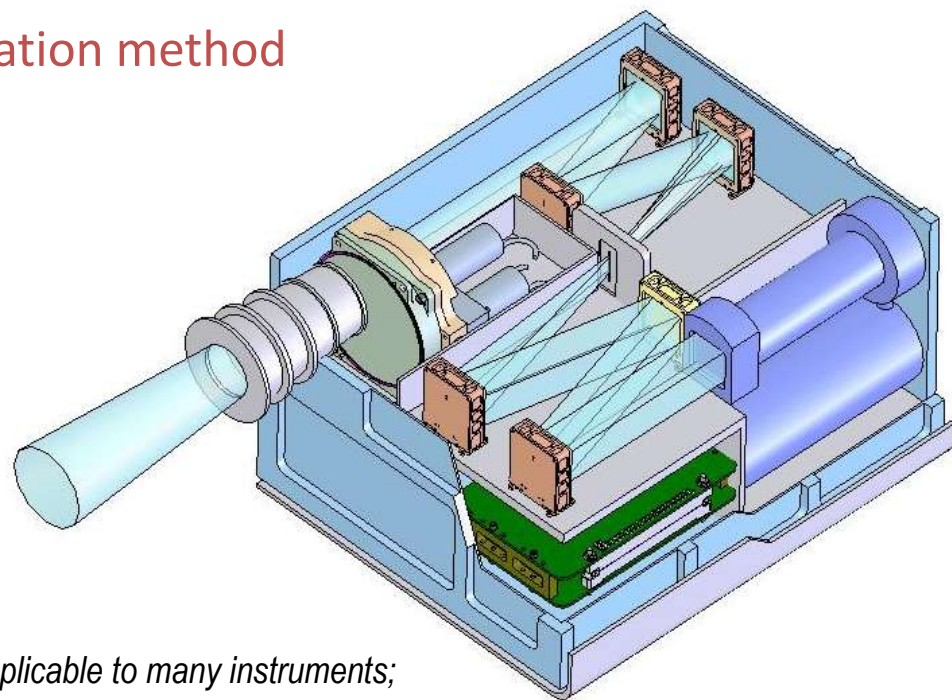
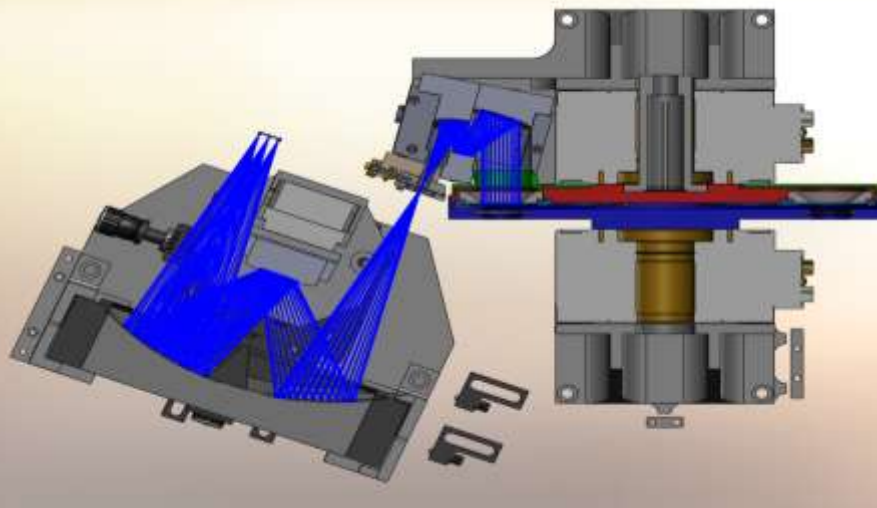
15° (180 km) (~370 pixels) Earth cross-track





IIP to Demonstrate Cross-Calibration Approach

- **Intent** is to demonstrate cross-calibration capability from spectral solar irradiance to desired accuracies
- **Method** is to prototype a visible (Si-based) hyperspectral spectrometer with integrated attenuation methods and
 - Demonstrate accurate attenuation capabilities
 - Show a solar irradiance observation method

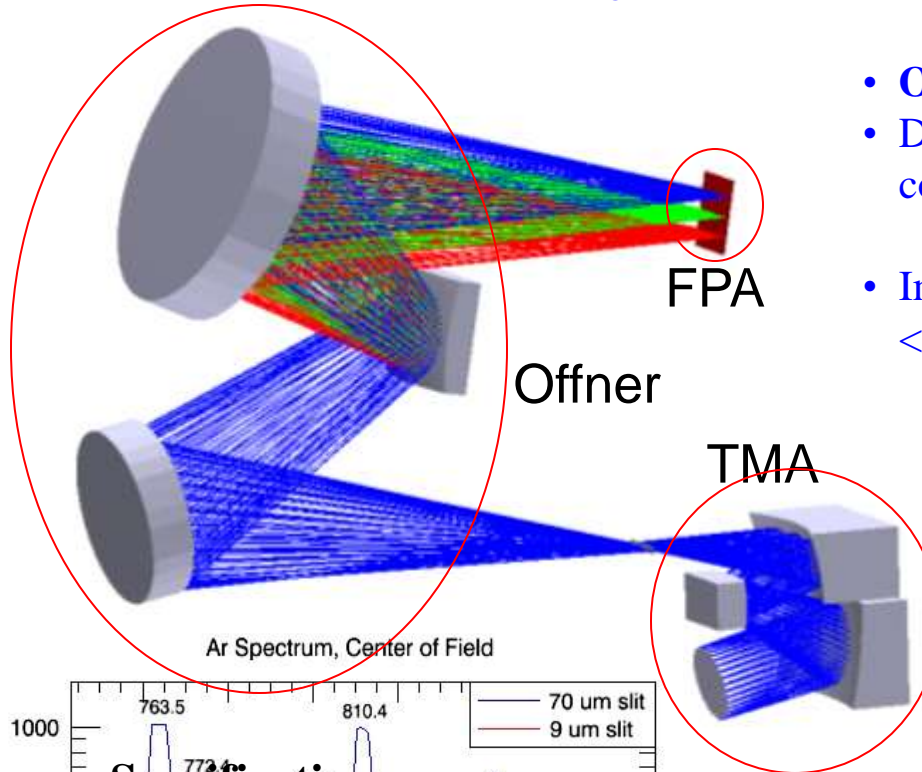


*Cross-calibration concept applicable to many instruments;
will be demonstrated in IIP using a hyperspectral imager.*

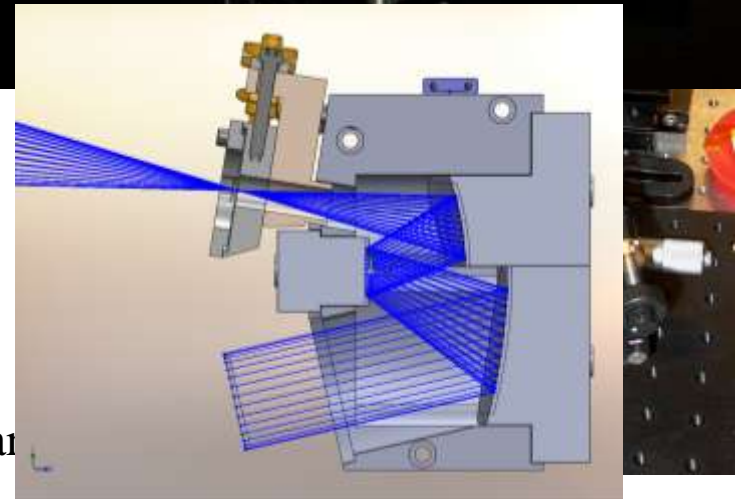


Overview of the Optical Design

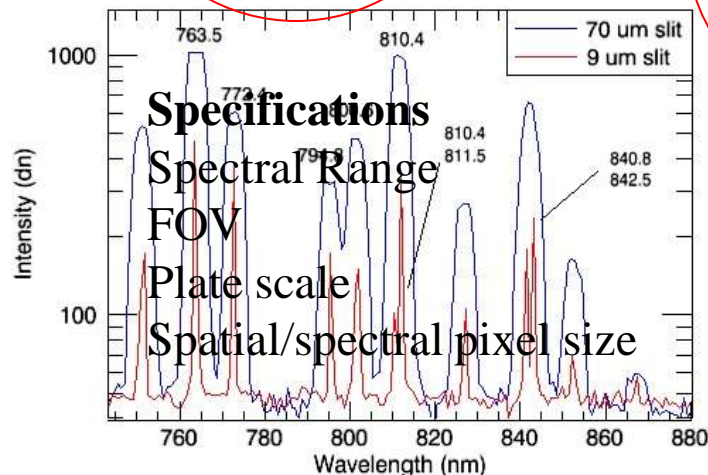
- **CMOS FPA** provides fast readout (to test integration time attenuations) and electronic shuttering (to eliminate image smear for accurate radiometry)



- **Offner spectrometer** provides spectral dispersion
- Designed around commercially available components for IIP proof-of-concept
- Imaging errors (aberration, smile, keystone) are <20% the effective pixel size.
- **Three mirror anastigmat (TMA)** images scene onto spectrometer slit



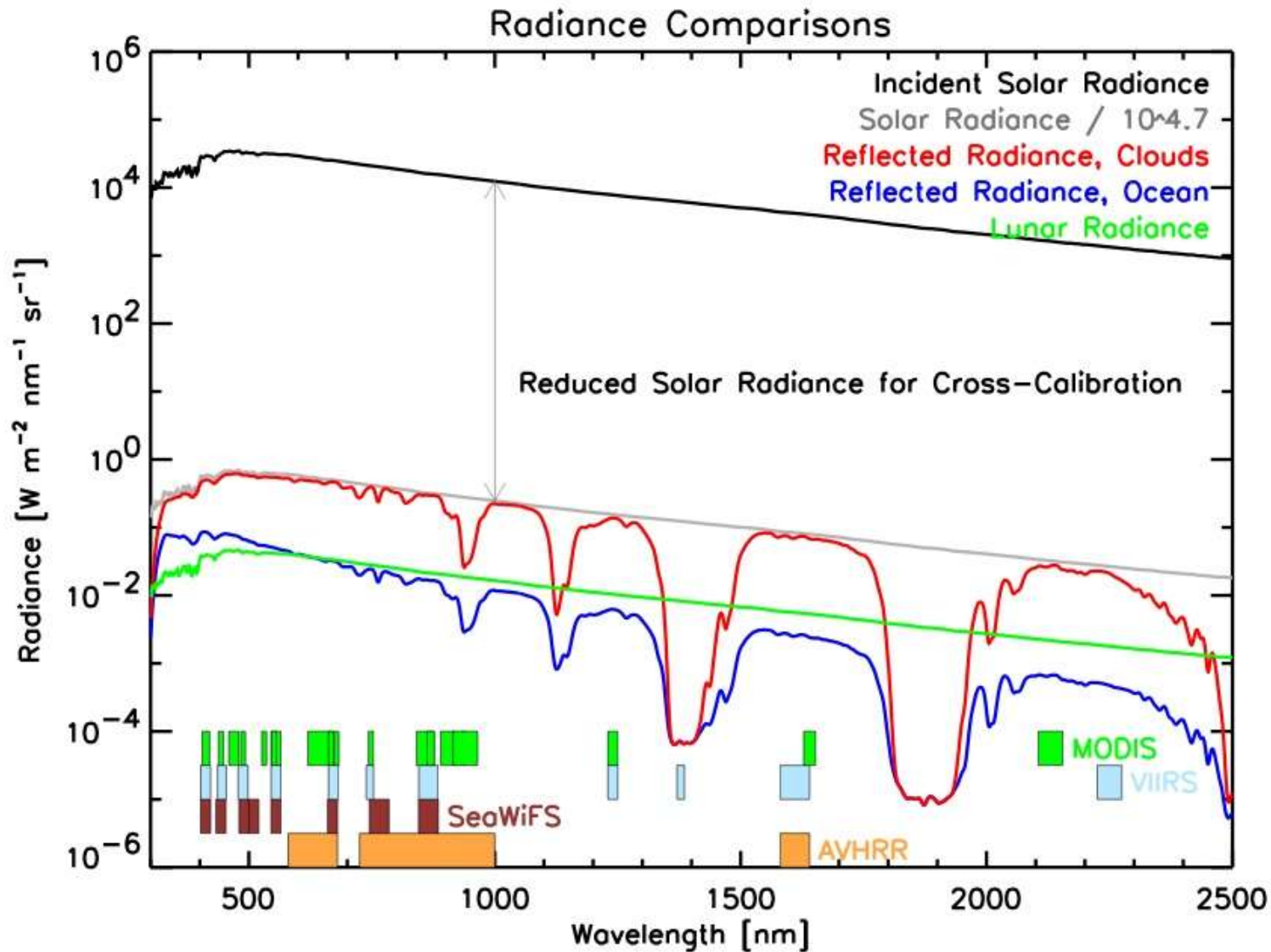
Ar Spectrum, Center of Field

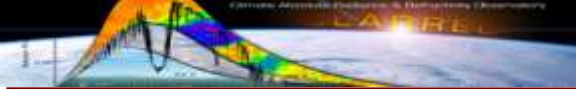


300-1100 nm
12.2°
0.79°/mm
52 μm \times 71 μm (2.5 arcmin)



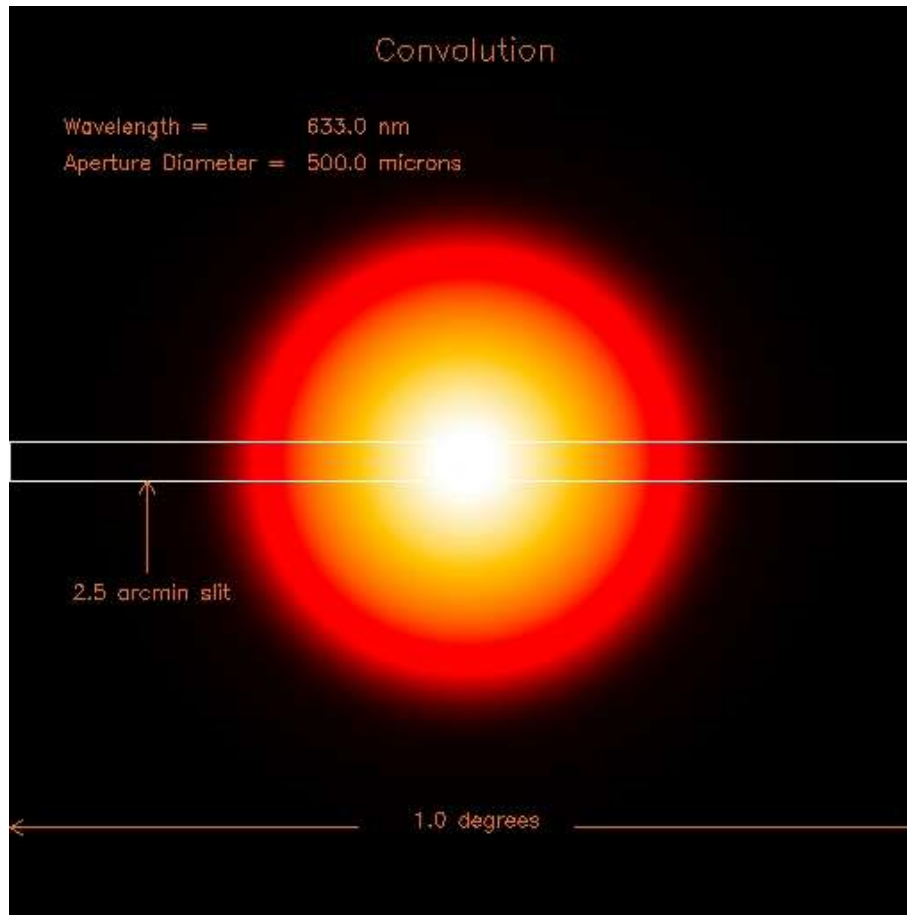
Need $\sim 10^{-5}$ Attenuation





Attenuation Methods Demonstrated With IIP

1. Aperture areas
 - 500- μm vs 2-cm diameter aperture attenuates light $10^{-3.2}$
 - NIST aperture area calibration achieves desired accuracy
2. Integration times
 - Diffraction limits attenuations achievable
3. Filters





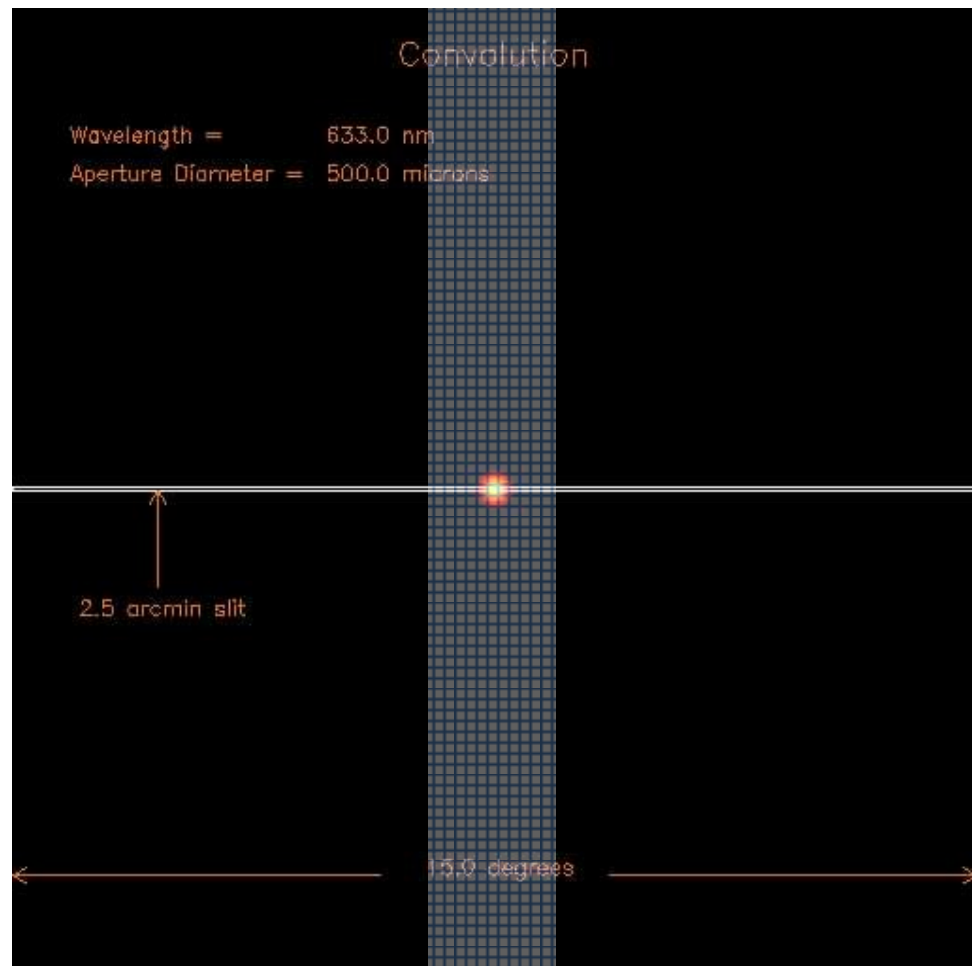
Attenuation Methods Demonstrated With IIP

1. Aperture areas

2. Integration times

3. Filters

- *High-speed and ROI read-out attenuate light 10^{-1}*
- *Electronics limit attenuations achievable*
- *Mechanical shutter may provide greater attenuations*

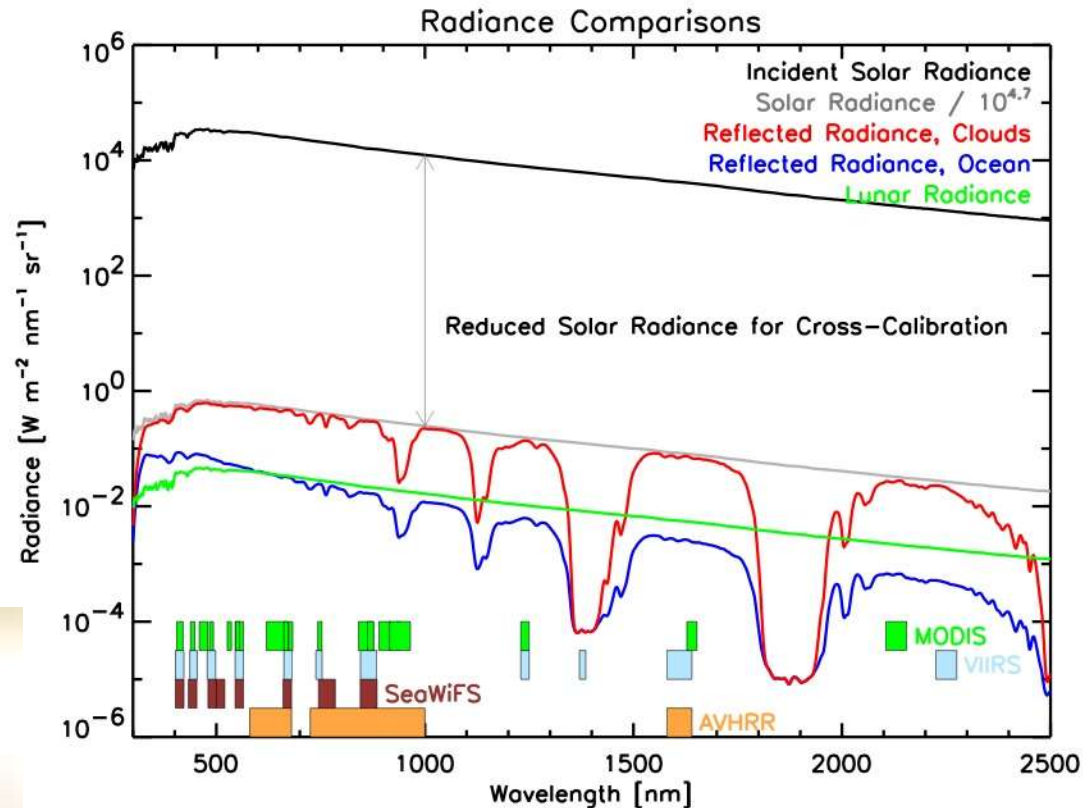
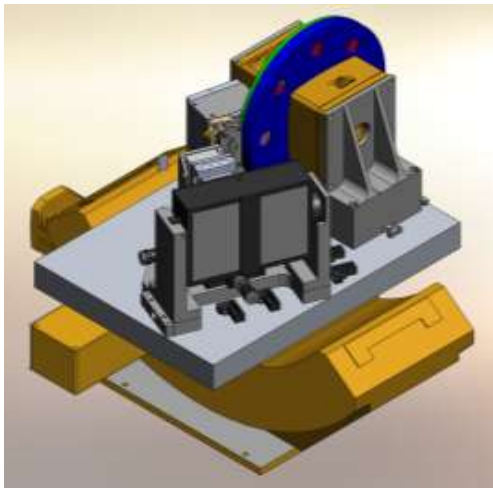




Attenuation Methods Demonstrated With IIP

1. Aperture areas
2. Integration times
3. Filters

- ND filters attenuate light 10^{-1} to 10^{-2}
- Filters are calibrated on-orbit via lunar observations
 - Same optical geometry as Sun
- Signal-to-noise limits attenuations achievable





Attenuation Validation Method

1. NIST calibrates photodiode detector for linearity across 10^6 range
 - Hamamatsu S6337-01 photodiode trap detector and paired Gamma Scientific transimpedance amplifier selected
2. Illuminate hyperspectral imager with Earth-like radiance level
 - Monitor high-power light source intensity with NIST-calibrated detector
3. Apply attenuation method
4. Increase light source intensity until hyperspectral imager reads original signal level
5. NIST-calibrated detector change in signal indicates actual attenuation magnitude and uncertainty
6. Repeat steps 3 to 5 for each attenuation method, demonstrating $10^{-4.7}$ net attenuation

Verdi Laser

Linear Polarizers

1/2 Waveplate

BEOC Stab
LPC-VIS

Spatial Filter

Linear Polarizer

1/4 Waveplate

BEOC Mon

Beam Splitter

Uniblitz Shutter
UHS1 (180usec)

Folding Mirror

Newport Refractive
Beam Shaper

Fast steering Mirror

Hyperspectral Imager

140 nW/cm² to
140 mW/cm²

0.07% Accuracy desired
Gamma Scientific TIA-3000
3 femtoamp dark
8 decades range
0.25% linearity for all ranges
W/Hamamatsu S6337
based trap detector

Provides stable, adjustable,
high-power beam

Creates spatially
uniform beam

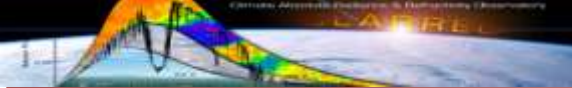
NIST-calibrated detector
monitors beam power over
10⁶ range

Other Equipment:
Beam expander 50-25-18X-lambda
Fast Steering Mirror, FSM-300-01
Diffusers

CMM Apertures/NIST on stage
Large aperture shutter - VS25 (3ms)
Post aperture lens -90mm F/4, UV-NIR NT-47-311
Photosciences Slit
Harold Johnson Spherical Mirror
JY Grating
CMOS or CCD
Uniblitz Shutter UHS1 (180usec)

Filter Wheel
Absorbing ND Filters
Schott NG12 & UG5

Joe Rice suggested
validations possible with HIP



Uncertainties Guide Attenuation Selections

Hyperspectral Imager Requirements

| Parameter | Value | Units |
|-----------------------------|-------|-------|
| Spatial Resolution | 0.5 | km |
| Spatial Range (cross-track) | 200 | km |
| Wavelength (min) | 300 | nm |
| Wavelength (max) | 2400 | nm |
| Spectral Resolution | 10 | nm |
| Relative Std Uncertainty | 0.2 | % |

Calibration Transfer Uncertainties

| Parameter | Value | Attenuation Amt. (Log) | Uncertainty |
|--------------------------------|-----------------------|------------------------|--------------|
| Aperture | 2 cm/500 μ m | 3.2 | 0.14% |
| <i>Aperture Ratio</i> | 1600.0 | 3.2 | 0.08% |
| <i>Diffraction</i> | | - | 0.10% |
| <i>Underfilled Optics</i> | | - | 0.05% |
| Integration Time | 0.07/0.002 s | 0.6 | 0.09% |
| <i>Elect. Integration Time</i> | 17 ms min | 0.6 | 0.09% |
| <i>Mech. Shutter Time</i> | 360 μ s min | 0.0 | 0.00% |
| Filter | ND 1 | 0.9 | 0.05% |
| <i>Lunar Meas. Accuracy</i> | meas. noise | | 0.02% |
| <i>Underfilled Optics</i> | | | 0.03% |
| <i>Surface Reflections</i> | 1° tilt | | 0.03% |
| <i>Linearity</i> | 0.05%/10 ² | | 0.02% |
| Linearity of Signal Levels | - | - | 0.05% |
| Noise | - | - | 0.10% |
| Polarization | 0.25% | - | 0.05% |
| Total | | 4.7 | 0.21% |

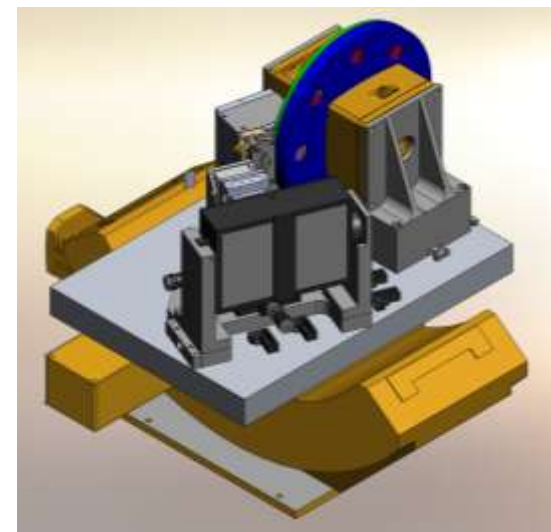


Summary

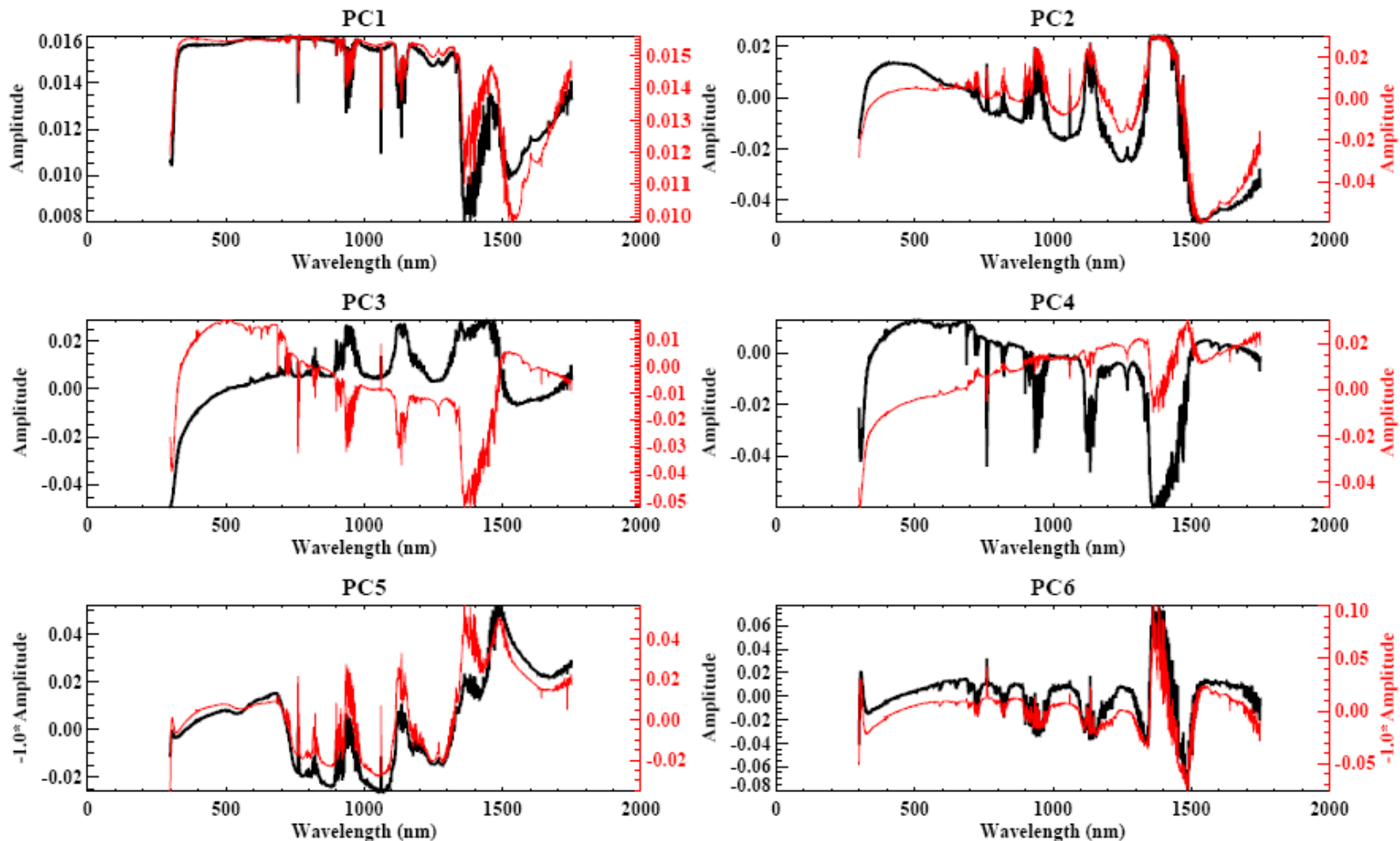
- IIP is addressing requirements similar to the LASP shortwave Science Study
 - Intended to demonstrate attenuation methods
- Cross-calibration approach using the Sun should give an on-orbit, SI-traceable measurement of Earth reflectance to needed accuracy levels for monitoring climate

Hyperspectral Imager Requirements

| Parameter | Value | Units |
|-----------------------------|-------|-------|
| Spatial Resolution | 0.5 | km |
| Spatial Range (cross-track) | 200 | km |
| Wavelength (min) | 300 | nm |
| Wavelength (max) | 2400 | nm |
| Spectral Resolution | 10 | nm |
| Relative Std Uncertainty | 0.2 | % |



PCA Components for Single and Global Orbits



This series of plots shows the comparison of the principal components derived from a global coverage data set for a single day from the SCIAMACHY data and radiances from a single orbit (12210) on the same day. The black lines represent the global coverage results, and the red lines represent the single orbit results.



Spectral Resolution

